

## 2.3 Active Fracture Concept

There is evidence that only a portion of the connected fracture network conducts water under unsaturated conditions. The fractures contributing to liquid flow are referred to as “active fractures”. The Active Fracture Concept (AFC) was developed by *Liu et al.* [1998] to describe gravity-dominated, non-equilibrium, preferential liquid flow in fractures, which is expected to be similar to fingering in unsaturated porous media. AFC is based on the hypothesis that (1) the number of active fractures is small compared with the total number of connected fractures, (2) the number of active fractures within a gridblock is large so that the continuum approach is valid, and (3) the fraction of active fractures,  $f_a$ , is related to water flux and equals one for a fully saturated system, and zero if the system is at residual saturation. The following power function of effective liquid saturation,  $S_e$ , fulfills these conditions:

$$f_a = S_e^\gamma \quad (2.3.1)$$

Here,  $\gamma$  is a positive constant depending on properties of the fracture network, and  $S_e$  is the effective liquid saturation given by

$$S_e = \frac{S_l - S_{lr}}{1 - S_{lr}} \quad (2.3.2)$$

Capillary pressure and relative permeability functions are modified to account for the fact that the effective saturation in the active fractures,  $S_{ea}$ , is larger than the effective saturation of the total fracture continuum:

$$S_{ea} = \frac{S_e}{f_a} = S_e^{1-\gamma} \quad (2.3.3)$$

Using the van Genuchten model, capillary pressure and liquid relative permeability are given, respectively, by

$$p_c = -\frac{1}{\alpha} \left[ S_e^{(\gamma-1)/m} - 1 \right]^{1/n} \quad (2.3.4)$$

and

$$k_{rl} = S_e^{(1+\gamma)/2} \left\{ 1 - \left[ 1 - S_e^{(1-\gamma)/m} \right]^m \right\}^2 \quad (2.3.5)$$

The fracture-matrix interface area reduction factor (see Section 2.1) is given by

$$a_{fm} = S_e^{1+\gamma} \quad (2.3.6)$$

The AFC is invoked by selecting  $\gamma > 0$ , which is provided as an additional parameter of the standard van Genuchten model (ICP=7) through variable CP(6,NMAT). Fracture-matrix interface area reduction according to Eq. (2.3.6) is invoked by selecting ISOT between -10 and -12.

The AFC is implemented by modifying the capillary pressure and relative permeability functions. The implementation is tested by directly comparing the values (i.e., saturation, capillary pressure, and relative permeability) given in the TOUGH2 output file with the ones calculated using Eqs. (2.3.2) through (2.3.5).

The TOUGH2 input file shown in Figure 2.3.1 is used for testing of the AFC as well as other requirements (see below).

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TOUGH2 input file for V&V of:
(1) Active Fracture Concept
(2) Modified Brooks-Corey function
(3) Modified van Genuchten function
(4) New observation type SECONDARY
(5) New observation type HEAT FLOW
(6) Handling of porosity
(7) ITOUGH2 application control

ROCKS-----1-----*-----2-----*-----3-----*-----4-----*-----5-----*-----6-----*-----7-----*-----8
AFC          2      2000.0      0.1      1.0E-12      1.0E-12      1.0E-12      2.0      900.0

      7      0.5000      0.1000      1.000
      7      0.5000      0.1000      0.001      1.0E+10      1.0      0.5
BC          2      2000.0      0.2      1.0E-12      1.0E-12      1.0E-12      2.0      900.0

      10      0.3000      0.1000
      10      2.0000      1000.0      0.100
VG          2      2000.0      0.3      1.0E-12      1.0E-12      1.0E-12      2.0      900.0

      11      0.3000      0.1000
      11      3.0000      1000.0      0.100
BC2         2      2000.0      0.2      1.0E-12      1.0E-12      1.0E-12      2.0      900.0

      10      0.2000      0.1000      1.0
      10      2.0000      1000.0      7000.0
VG2         2      2000.0      0.3      1.0E-12      1.0E-12      1.0E-12      2.0      900.0

      11      0.2000      0.1000      1.0
      11      3.0000      1000.0      7000.0      0.3

PARAM-----1-----*-----2-----*-----3-----*-----4-----*-----5-----*-----6-----*-----7-----*-----8
      3      1      110000801000000000400001000
                  1.0

                  1.0E5                  10.3                  20.0
MULTI-----1-----*-----2-----*-----3-----*-----4-----*-----5-----*-----6-----*-----7-----*-----8
      2      3      2      6
ELEME-----1-----*-----2-----*-----3-----*-----4-----*-----5-----*-----6-----*-----7-----*-----8
ELM 1          AFC          0.1
ELM 2          BC          0.1
ELM 3          VG          0.1

CONNE-----1-----*-----2-----*-----3-----*-----4-----*-----5-----*-----6-----*-----7-----*-----8
ELM 1ELM 2          -10      0.05      0.05      0.10
ELM 2ELM 3          1      0.05      0.05      0.10

START-----1-----*-----2-----*-----3-----*-----4-----*-----5-----*-----6-----*-----7-----*-----8
INCON-----1-----*-----2-----*-----3-----*-----4-----*-----5-----*-----6-----*-----7-----*-----8
ELM 1          0.4
      1.1E5          10.3          50.0
ELM 2          0.5
      1.0E5          10.3          20.0

ENDCY-----1-----*-----2-----*-----3-----*-----4-----*-----5-----*-----6-----*-----7-----*-----8

```

**Figure 2.3.1.** TOUGH2 input file vv used for testing of Active Fracture Concept, modified Brooks-Corey and van Genuchten functions, newly implemented observation types, and handling of porosity.

The parameters used for the AFC as given in the TOUGH2 input file (see Figure 2.3.1) are summarized in Table 2.3.1.

**Table 2.3.1.** Parameters of AFC

Parameter	TOUGH2 Parameter	Value
$S_{lr}$	RP(2), CP(2)	0.10
$\gamma$	CP(6)	0.50
$\alpha$	CP(3)	0.001
$m$	RP(1), CP(1)	0.50
$n = 1 / (1 - m)$	-	2.00
$k$	PER(1)	1.0E-12
$A$	AREAX	0.10
$d_1, d_2$	DEL1, DEL2	0.05

Figure 2.3.2 shows an excerpt from the TOUGH2 output file vv.out, which is obtained by running the problem with the following command line:

```
tough2 -v 3.2 vv 3 &
```

The liquid saturation in gridblock “ELM 1”, to which the AFC characteristic curves are assigned, is 0.69998. Inserting this value along with the parameters of Table 2.3.1. into Eqs. (2.3.2), (2.3.4), and (2.3.5) yields the following capillary pressure and liquid relative permeability:

$$S_e = \frac{0.69998 - 0.1}{1 - 0.1} = 0.66664$$

$$p_c = -\frac{1}{0.001} \left[ 0.66664^{(0.5-1)/0.5} - 1 \right]^{1/2.0} = -707.15$$

$$k_{rl} = 0.66664^{(1+0.5)/2} \left\{ 1 - \left[ 1 - 0.66664^{(1-0.5)/0.5} \right]^{0.5} \right\}^2 = 0.13177$$

These values are consistent with the ones reported in the TOUGH2 output file (Figure 2.3.2).

The fracture-matrix interface area reduction factor (see Section 2.1) is given by Eq. (2.3.6):

$$a_{fm} = 0.66664^{1+0.5} = 0.5443$$

Applying Darcy’s law between gridblocks “ELM 2” and “ELM 1” yields:

$$\begin{aligned}
q_{ELM2-ELM1} &= -k \cdot A \cdot a_{fm} \frac{k_{rl}}{\mu_l} \rho_l \left( \frac{p_{ELM1} - p_{ELM2}}{d_1 + d_2} \right) \\
&= -10^{-12} \cdot 0.1 \cdot 0.5443 \frac{0.13177}{5.4418 \cdot 10^{-4}} 988.07 \left( \frac{1.0704 \cdot 10^5 - 1.0002 \cdot 10^5}{0.05 + 0.05} \right) \\
&= -9.142 \cdot 10^{-4} \text{ kg / s}
\end{aligned}$$

which is consistent with the liquid flux at the first connection. These results fulfill Requirement 3.